

## MEASUREMENT OF MASSES AND LIFETIMES OF B HADRONS

F. FILTHAUT for the DØ and CDF Collaborations  
*Radboud University, Nijmegen and NIKHEF*  
*Toernooiveld 1, 6525 ED Nijmegen, The Netherlands*

We present recent measurements by the CDF and DØ Collaborations at the Tevatron Collider on the masses and lifetimes of B hadrons. The results are compared to predictions based on Heavy Quark Effective Theory, lattice gauge theory, and quark models.

*Keywords:* hadrons, spectroscopy, lifetimes, Tevatron

### 1 Introduction

The ongoing Run II at the Tevatron  $p\bar{p}$  Collider at the Fermi National Accelerator Laboratory has produced a wealth of results on B-physics. While the physics of  $B_d$  and  $B^\pm$  mesons is largely the domain of the  $e^+e^-$  B-factories operating at the  $\Upsilon(4S)$  resonance, access to the heavier B hadrons is presently reserved exclusively for the Tevatron. The drawback of working in the less clean hadron collider environment is more than compensated for by the high total  $b\bar{b}$  production cross section (of order  $100 \mu\text{b}$ ) and the high luminosity (the integrated luminosity delivered to the CDF and DØ experiments to date is of order  $2 \text{ fb}^{-1}$ ).

In the following, we discuss recent results obtained thanks to the high statistics B samples. Sect. 2 discusses new excited states that have been identified in the B,  $B_s$ , and  $\Lambda_b$  systems. Sect. 3 covers a number of new and precise lifetime measurements. The measurements have been made on data samples of integrated luminosity ranging from 0.3 to  $1.3 \text{ fb}^{-1}$ . The two experiments' results are compared, both with each other and theoretical predictions.

### 2 Spectroscopy

#### 2.1 Orbitally excited B and $B_s$ mesons

The spectroscopy of bound states containing one heavy quark ( $Q$ ) and a light antiquark<sup>a</sup> is of great interest to quark models, as the dynamics of the light antiquark becomes independent of  $m_Q$ , and the total and light quark's angular momentum become good independent quantum numbers. However, low statistics prevented the  $L = 1$  orbitally excited  $B^{**}$  states from being investigated in great detail previously.

The  $B^{**}$  system is thought to consist of four states, two of which have a light quark angular momentum  $J_q = 1/2$ ; their decay to  $B^{(*)}\pi$  proceeds via an  $S$ -wave, and their total decay width is expected to be  $\mathcal{O}(100\text{MeV})$ , too wide to be observed unambiguously. The  $J_q = 3/2$   $B_1$  and

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<sup>a</sup>Here and in the following, charge conjugated states are implied.

$B_2^*$  states (with total spin 1 and 2, respectively) decay via a  $D$ -wave, and their width, of order 10 MeV, should allow them to be identified clearly.

Both experiments have searched for the  $B_1$  and  $B_2^*$  states, through the decays  $B_1^0 \rightarrow B^{*+}\pi^-$  and  $B_2^{*0} \rightarrow B^{(*)+}\pi^-$ . The photon from the decay  $B^{*+} \rightarrow B^+\gamma$  is not observed, resulting in two  $B_2^*$  peaks in the  $B\pi$  invariant mass spectrum, displaced by 46 MeV. Both experiments identified  $B^+$  mesons through their decay to  $J/\psi K^+$ , the  $J/\psi$  being recognized easily in its decay to muons; in addition, CDF employed the decay  $B^+ \rightarrow \bar{D}^0\pi^+$ .

The resulting  $B\pi$  invariant mass spectra, for the  $J/\psi K^+$  decay mode, are shown in Fig. 1. CDF's results are consistent with those using the  $\bar{D}^0\pi^+$  mode. The two experiments' results obviously disagree: while DØ find clear evidence for three separately observed peaks, CDF find that the  $B_1^0$ ,  $B_2^{*0} \rightarrow B^{*+}\pi^-$  peaks coincide. The resulting  $B_1^0$ - $B_2^{*0}$  mass splittings (25 MeV and 4 MeV, respectively) both disagree with the theory prediction of 12–14 MeV<sup>1</sup>.

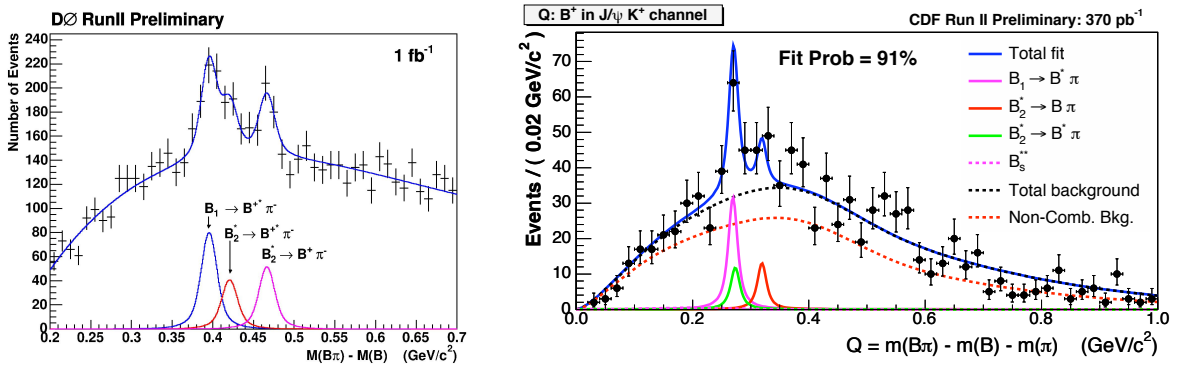


Figure 1: Distributions of the invariant mass difference  $m(B\pi) - m(B)$  (left) for DØ, and  $m(B\pi) - m(B) - m(\pi)$  (right) for CDF, reconstructed in the mode  $B^+ \rightarrow J/\psi K^+$ .

Both experiments have also carried out analogous analyses of  $B_s^{*0} \rightarrow B^+K^-$  decays. The  $B_s^{**}$  system is expected to replicate that of the  $B^{**}$ . However, the decay  $B_{s2}^{*0} \rightarrow B^{*+}K^-$  is expected to be suppressed strongly, so that at most two peaks should be discernible. The results obtained are shown in Fig. 2. Both experiments find a very clear peak around 67 MeV, which is attributed to

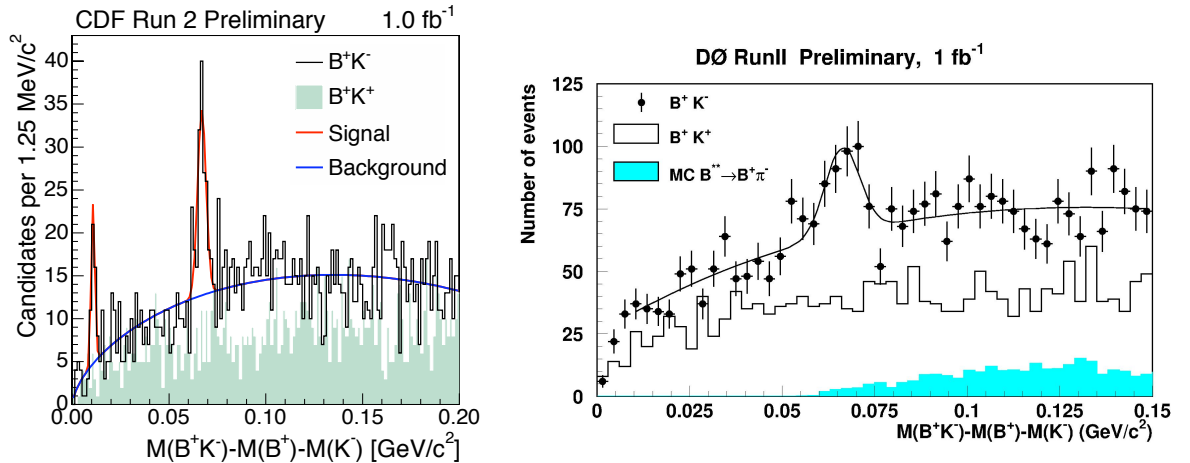


Figure 2: Distributions of the invariant mass difference  $m(BK) - m(B) - m(K)$  for CDF (left) and DØ (right).

$B_{s2}^{*0} \rightarrow B^+K^-$  decays. In addition, CDF find evidence for  $B_{s1}^0 \rightarrow B^{*+}K^-$  decays, at a  $Q$ -value of 11 MeV (DØ would not expect to observe a  $B_{s1}^0$  peak, given their observed mass splitting in the  $B$  system). The resulting mass splitting of 10 MeV is fairly consistent with theoretical predictions.

Summarizing, both experiments obtain results consistent between B and  $B_s$ ; however, there is a lack of agreement between CDF and  $D\emptyset$ .

## 2.2 $\Sigma_b$ baryons

CDF have used a sample of fully reconstructed  $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$  decays to search for  $\Sigma_b$  baryons, in the decay  $\Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0 \pi^\pm$ . In these baryons, the light di-quark system has  $I = 1$  and  $J^P = 1^+$ ; adding the b quark leads to  $J^P = \frac{1}{2}^+$  ( $\Sigma_b$ ) and  $J^P = \frac{3}{2}^+$  ( $\Sigma_b^*$ ). The  $\Sigma_b$ - $\Lambda_b$  mass difference is expected to be  $\sim 200$  MeV. The mass splitting between the systems is expected<sup>2</sup> to be  $m(\Sigma_b^*) - m(\Sigma_b) = m_c/m_b \cdot (m(\Sigma_c^*) - m(\Sigma_c)) \approx 20$  MeV; also a small splitting between states within the same isospin triplet is expected.

In the analysis, the total decay widths are assumed to be saturated by single pion transitions, and constrained to the theory expectation of  $\sim 8$  MeV and 15 MeV for the  $\Sigma_b$  and  $\Sigma_b^*$ , respectively<sup>3</sup>. In addition, the isospin splittings are assumed to be the same for  $\Sigma_b$  and  $\Sigma_b^*$ . The result is shown in Fig. 3, and is in good agreement with theory predictions:  $m(\Sigma_b^-) = 5816 \pm 1 \pm 1.7$  MeV,  $m(\Sigma_b^+) = 5808_{-2.0}^{+2.3} \pm 1.7$  MeV,  $m(\Sigma_b^{*-}) = 5837_{-1.9}^{+2.1} \pm 1.7$  MeV,  $m(\Sigma_b^{*+}) = 5829_{-1.8}^{+1.6} \pm 1.7$  MeV. (Note

that not all of these results are independent.)

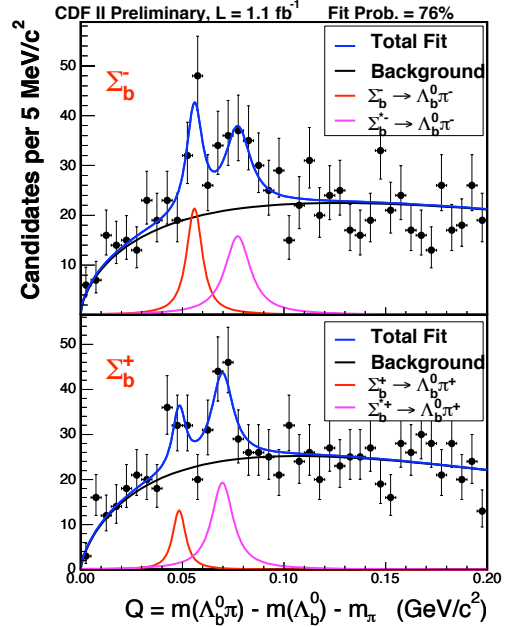


Figure 3: Distribution of the mass difference  $m(\Lambda_b \pi) - m(\Lambda_b) - m(\pi)$  for same-charge and opposite-charge  $\Sigma_b$  signals.

## 2.3 The $B_c$ meson

The  $B_c$  meson, the lowest mass bound state of a b and c quark, has been observed already at LEP and in Run I of the Tevatron. However, only two fully reconstructed event candidates were observed so far<sup>4</sup>, in the decay mode  $B_c^+ \rightarrow J/\psi \pi^+$ . The resulting uncertainty on the mass was relatively large, about 60 MeV. CDF have now used this same decay mode in their Run II data sample, requiring in addition that the  $J/\psi$  decay vertex be significantly displaced from the interaction point. They observe a signal of  $49.1 \pm 9.7$  events over a background of 34.1 events. The result of the mass fit is  $m(B_c) = 6276.5 \pm 4.0(\text{stat.}) \pm 2.7(\text{syst.})$  MeV. This represents an improvement of an order of magnitude in accuracy over previous results.

## 3 Lifetimes

Heavy Quark Effective Theory allows for a systematic expansion in orders of  $\alpha_s$  and  $1/m_Q$  of the total decay widths of heavy-quark hadrons. As a result, precise predictions have been made for the ratios of lifetimes of B hadrons. In the past, this led to the so-called “ $\Lambda_b$  puzzle”, where the measured  $\Lambda_b$  lifetime ratio  $\tau(\Lambda_b)/\tau(B_d)$  was significantly below its theoretical expectation. Improved lattice gauge theory computations have since been made of B-hadron lifetimes<sup>5</sup>, and they have decreased this theoretical expectation substantially to  $0.88 \pm 0.05$ , in fair agreement with experiment.

Both CDF and DØ have measured  $\tau(\Lambda_b)$  in the exclusive decay  $\Lambda_b \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\Lambda(\rightarrow p\pi)$ . This decay is very similar to the decay  $B_d \rightarrow J/\psi K_S(\rightarrow \pi^+\pi^-)$ , allowing for a “calibration” of the analyses using the precisely known  $B_d$  lifetime. The  $J/\psi$  decay vertex is combined with the reconstructed  $\Lambda$  ( $K_S$ ) track to yield the  $\Lambda_b$  ( $B_d$ ) vertex in the plane perpendicular to the beam line; correcting for the boost yields the lifetime estimate. Simultaneous unbinned maximum likelihood fits were made to the invariant mass and lifetime distributions (and given that event-by-event lifetime resolution estimates are used, the lifetime resolution distribution).

Both experiments measure a  $B_d$  lifetime compatible with the world average. For the  $\Lambda_b$ , DØ’s measurement,  $\tau(\Lambda_b)/\tau(B_d) = 0.811_{-0.087}^{+0.096}(\text{stat.}) \pm 0.034(\text{syst.})$  is compatible with previous measurements and the theoretical predictions. However, the purer and more precise CDF result,  $\tau(\Lambda_b)/\tau(B_d) = 1.018 \pm 0.062(\text{stat.}) \pm 0.007(\text{syst.})$ , is much higher than previous estimates.

DØ have measured the same quantity in the inclusive semileptonic decay  $\Lambda_b \rightarrow \Lambda_c \mu^- \bar{\nu}_\mu X$ . This measurement differs in many respects: it uses large statistics, but as it is an *inclusive* measurement a  $\Lambda_b$  peak is not observed. Instead, the  $\Lambda_c$  is reconstructed in its decay mode  $\Lambda_c \rightarrow K_{Sp}$ . It is observed on top of a large background, which is subtracted statistically, in bins of the visible proper decay length. This quantity is corrected for the particles not reconstructed in the  $\Lambda_b$  decay, the correction being modeled by Monte Carlo simulations. The result,  $\tau(\Lambda_b) = 1.28_{-0.11}^{+0.12}(\text{stat.}) \pm 0.09(\text{syst.})$  ps, is in good agreement with DØ’s measurement in the  $J/\psi\Lambda$  channel. In conclusion, the “ $\Lambda_b$  puzzle” cannot yet be considered resolved – but at least we know there is an *experimental* issue to be addressed!

CDF have used their  $J/\psi$  sample to measure also other lifetimes in exclusively reconstructed decays. In particular, using the decays  $B^+ \rightarrow J/\psi K^+$  and  $B_s^0 \rightarrow J/\psi \phi$ ,  $\phi \rightarrow K^+K^-$ , they find  $\tau(B^+) = 1.630 \pm 0.016(\text{stat.}) \pm 0.011(\text{syst.})$  ps and  $\tau(B_s^0) = 1.494 \pm 0.054(\text{stat.}) \pm 0.009(\text{syst.})$  ps, respectively. These measurements are in good agreement with earlier measurements, as well as with HQET predictions. Similarly, a new DØ measurement of the  $B_s$  lifetime using  $B_s^0 \rightarrow D_s^- \mu^+ \nu_\mu X$  decays, with the  $D_s^-$  identified through  $D_s^- \rightarrow \phi \pi^-$ ,  $\phi \rightarrow K^+K^-$ , yields  $\tau(B_s^0) = 1.398 \pm 0.044(\text{stat.})_{-0.025}^{+0.028}(\text{syst.})$  ps. This is in fair agreement with the current world average result. It should be pointed out that both experiments’ new  $B_s$  results have accuracies comparable to the present world average, offering good hopes for more incisive tests of HQET.

Finally, CDF carried out a partial reconstruction of the decay  $B_c^+ \rightarrow J/\psi(\rightarrow \mu^+\mu^-)e^+\nu_e X$ . The  $B_c$  lifetime is expected to be much shorter,  $\tau(B_c) = 0.48 \pm 0.05$  ps<sup>6</sup>, than that of the other weakly decaying B hadrons, because also the charm quark can decay. The analysis attempts to isolate the exclusive decay  $B_c^+ \rightarrow J/\psi e^+ \nu_e$  using tight kinematic cuts. The challenge is a proper understanding the instrumental backgrounds (many of which are non-prompt), inferred from data, and from  $b\bar{b}$  production, estimated using MC. The result,  $\tau(B_c) = 0.463_{-0.065}^{+0.073}(\text{stat.}) \pm 0.036(\text{syst.})$  ps, is in good agreement with the present world average,  $\tau(B_c) = 0.46_{-0.16}^{+0.18}(\text{stat.}) \pm 0.03(\text{syst.})$  ps. The new result is the most precise one to date, and its accuracy approaches that of the theoretical predictions.

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